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RELIABILITY OF ZIRCONIA TOUGHENED ALUMINA (ZTA) CERAMICS CUTTING TOOLS WHILE MACHINING HARDENED STEELS OF 340 BHN IN HIGH SPEED MACHINING

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ABSTRACT

Experiments were carried out on Zirconia Toughened Alumina (ZTA) based ceramic cutting tools at various cutting speeds ranging from 100 to 400 m/min on the hardened steels of about 340 BHN. Turning tests were carried out using CNC Heavy Duty Horizontal Machining Center for reliability of the tools. ZTA samples were prepared by powder processing technique. Weibull analysis and Anderson Darling Techniques have been used for the reliability analysis using Minitab software. The reliability tests proved that the tools are consistent in their performance and gave satisfactory results.

KEYWORDS: ZTA, Hardened Steel, Flank Wear, Reliability, Weibull & Anderson-Darling Test

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Original Article

1. INTRODUCTION

High speed machining process is used in many of the automobile and aerospace industries. These industries require high precision machine, capable of machining hardened steels coupled with high metal removal rate with good surface finish.

Xiaobin Cui et al [1] have focused on reliability analysis and statistical and damage analysis models, of Ceramic cutting tool in continuous and interrupted machining on the AISI 1045 hardened steel at a cutting speed of 110m/min. Various probability graphs were drawn to estimate the tool reliability by taking flank wear as reference.

Christophe Letotetal [2] explained various Reliability approaches that affect the flank wear of cutting tool. These approaches include failure time approach caused by the failure of cutting tool while machining, besides Power consumption. They have carried the machining on the Grey cast iron having of 322 HV with Tungsten carbide insert at cutting speed of 340 m/min.

Konstantinos Salonitisa et al [3] have proposed advanced approximation methods that influence the effect of cutting tool life and flank wear of the tool, and used various probability plots and reliability techniques like Monte Carlo simulation of first and second order. He worked on high carbon steel, C 55Work piece material with

Tungsten carbide insert at cutting speeds of 300,400 and 500 m/min.

Srinivasa Varma et al [4] have focused on the performance of ZTA ceramic cutting tools on the 0.31% Carbon steel material having hardness of about 180 BHN at various cutting speeds. Reliasoft software was used for the prediction of tool life using Weibull distribution. He has evaluated the behavior of cutting tools at different cutting speeds.

Siva Bhaskar et al [5] presented the optimal tool replacement time of the tool performance by using the reliability function and the various probability distributions that fit the data by using Minitab software. They have carried out the work on Inconel 718 using cemented carbide inserts and used Minitab software.

Lin et al [6] focused on the probability function that affects the reliability of cutting tools. The reliability of hazard function effect on the cutting tool wear and tool life of cutting tool were used to estimate the remaining time tool life. They have carried out the work on High carbon steel material and used Carbide inserts for the experiments.

Klim et al [7] have proposed a method of variable feed milling to improve the cutting tool life in continuous and hard machining. They have carried out of reliability of Carbide inserts on Stainless steel at cutting speed of 92 m/min and studied the effect of feed variation on flank wear and tool life.

Lin et al [8] described the reliability of cutting tools in machining by normal distribution method in high speed machining process on high carbon steel using tungsten carbide inserts.

1.1 Reliability as Applied to Cutting Tools

Reliability can be defined as the capability of an item to perform, or to be capable of performing a required function without the failure under stated conditions for a stated period of time or unit of operation. Reliability can be applied to various engineering applications such as automobile, aerospace, life of bearings or cutting tools as discussed by Sekulic [9].

The intended approach of reliability is defined as the probability that an item can perform a required function under the stated condition/s for a specific period of time. Reliability can be expressed between zero and one, where zero represents certain failure and one indicates success in the accepted manner. Consider reliability, denoted as a probability of success, by the symbol R, and the probability of failure by the symbol F. then

$$R+F = 1$$

The mathematical approach to estimate reliability, a number of statistical distributions used, usually, Negative exponential distribution. Constant failure rate can be represented by this distribution very successfully. However, it can be limited for application, particularly for mechanical properties. Many real distributions do not correspond to the negative exponential, and significant errors could arise by forcing them into this method, as discussed by Daiict[10].

The Weibull and lognormal distribution fills this requirement, because it can be made to approximate very closely to the normal distribution. It is again very valuable for the same reason quoted in the case of the negative exponential distribution. Since it can stand in for both negative exponential and the normal distribution besides representing many other real ones, the Weibull distributions and lognormal is adopted in the work of the reliability of ceramic cutting tools which was discussed by Carter [11].

1.2 Description of Experiment

The estimation of the reliability data depends on the variable and attributes data. The tests that are conducted by life time called variable data and data recorded at a specific time of failures is called attribute data.

The data needed for any reliability tests are (i) time censored test (ii) failure censored test.

In time censored test, the number of failures that are occurred over a specific period of time, in case of failure censored test it occurs failure at a period of time as discussed by Troitsky et al [12] and Robert [13].

We have adopted failure censored test for tools, taking flank wear as the criteria besides surface roughness during turning operation on lathe. We have found out that Tool wear is irregular. Hence, we have taken V_B=0.6mm as failure criteria as was discussed by Dimitri [14]. Additionally, we have noticed that the surface roughness ~ 1.6 microns (R_a) can be achieved up to 0.6 mm flank wear.

2. EXPERIMENTAL PROCEDURE

2.1 Tool Material

Zirconia Toughened Alumina ceramic inserts were used in present experiments. ZTA tools were fabricated from submicron powders consisting of 85 Volume% Alumina and 15 Volume% of Zirconia. The properties were shown in Table 1 below.

Table 1: Cutting Insert Properties

Tool Material	Density(g/cm^3)	Hardness HV20	Fracture Toughness (Mpa) m$^{1/2}$
ZTA	4.156	1700	6.5

2.2 Workpiece Material Composition and Specifications

The work material used in machining was hardened steel, and has the following composition as shown in Table 2. The specifications of the workpiece are given in table 3.

Table 2: Chemical Properties of Work Material in (%)

Cr	Mn	C	Si	Mo	V
2.7	0.6	0.23-0.35	0.5	0.25	0.05

Table 3: Specifications of Work Material

Work Piece Material	Hardened Steel
Diameter	110 mm
Length	500 mm
Hardness	340 BHN

2.3 Cutting Tool Specifications

Tool holder and Tool insert specifications used in this experiment were as follows:

Tool Holder – Sandvik T max R 174.1-2020-12

Tool Insert – SNUN 120412

2.4 Experimental Setup and Cutting Conditions

Turning tests were carried out by using Lokesh CNC Heavy Duty Horizontal Machining Center, HML 630**,** having speed range of 50-5000 rpm**,** 22.5 kW spindle power and having torque of 239 N-m by using different cutting speeds under dry condition. The details are given in table 4.

Table 4: Cutting Parameters at Various Cutting Speeds

Test	Cutting Speed, m/min	Feed, mm/rev	Depth of Cut, mm	Work Material, BHN	Nose Radius	Tool
Test-1	100	0.1	0.5	340	1.2	ZTA
Test-2	140	0.1	0.5	340	1.2	ZTA
Test-3	200	0.1	0.5	340	1.2	ZTA
Test-4	280	0.1	0.5	340	1.2	ZTA
Test-5	400	0.1	0.5	340	1.2	ZTA

2.5 Methodology of Application of Reliability Using Minitab

The probability of life/failure is estimated using statistical analysis. There are many software available for reliability to find how the component survives in specified conditions over a period of time as per ISO 3685:1993(Revised 2017) [15].

In this work, the following steps were taken

- Identifying the cutting parameters that influence the flank wear and tool life.
- Adopting the criteria that most suits the data for carrying the analysis.
- Finding the reliability based on the data.

Besides, Statistical distribution that is the best fit for a given set of values, the reliability concepts like exact failure time, Right censored failure time and left censored failure and interval censored failure time are also taken into consideration.

In Present work, right censoring failure time deals with particular time the sample failed(until not failed by that time). Curves of Probability density function that shows the relative probability of the failure time and Survival function that shows the probability of unit surviving at a particular period of time is also carried out.

Hazard rate function indicates that the probability of failure that shows the probability of a unit failing at that particular time, given time it is survived until the failure time.

Totally, 50 tools inserts were used for machining purpose. Experiments were done on dry machining conditions (without lubricant). Time and Flank wear taken, until the cutting tool to be worn out to 0.6mm on flank.

In the analysis part, the steps are considered to identify the best distribution for the experimental readings and obtain the probability plots like Weibull and lognormal and probability density function and survival function.

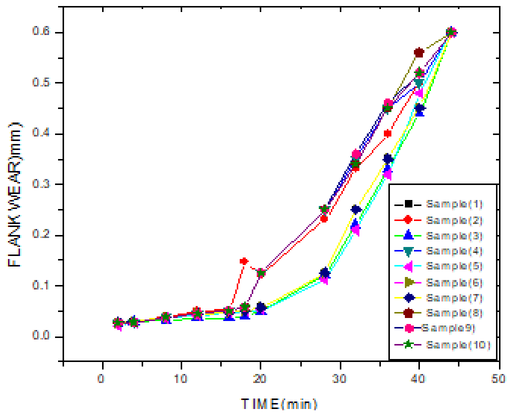
Tests are conducted by Goodness of fit (based up on Anderson-darling test), and the lognormal distribution for shape and scale parameters were analyzed from the dataas predicted by Kishore Kumar Pochampally et al [16].

3. RESULTS AND DISCUSSIONS

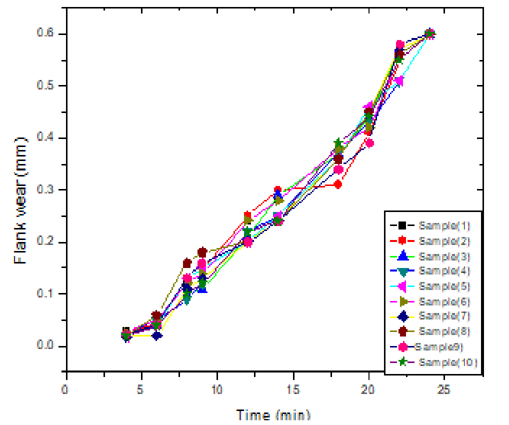
3.1 Flank Wear at Different Speeds

Figure 1 shows that the Flank wear of cutting tools at a regular interval of time with the different cutting speeds. The curves show all three wear mechanisms namely (i) the initial rapid wear (ii) gradual wear and (iii) failure wear. Cutting speed play a prominent role in machining the hard material, as the cutting speed increases, flank wear also increased. Flank

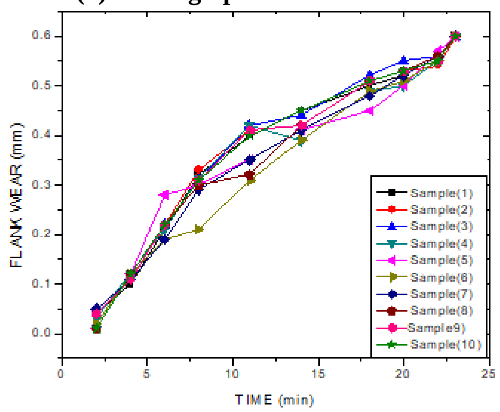
wear is time dependent process. Each of the graph shows that ten samples of ZTA at one cutting speed ranging from 100m/min to 400 m/min.



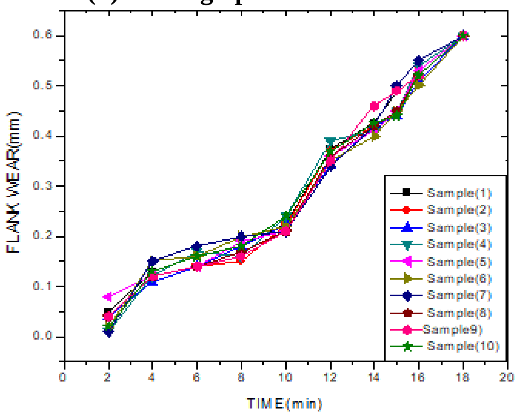
(a) Cutting Speed: 100 m/min



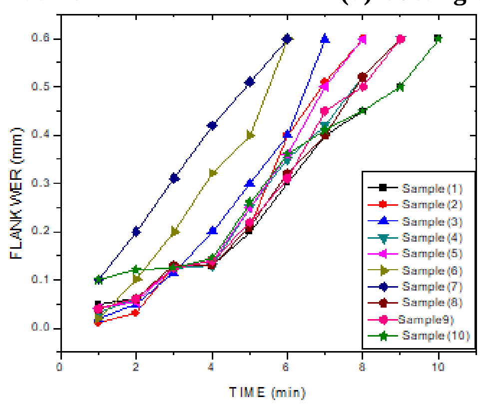
(b) Cutting Speed: 140 m/min



(c) Cutting Speed: 200 m/min



(d) Cutting Speed: 280 m/min



(e) Cutting Speed: 400 m/min

Figure 1: Tool Flank Wear at Different Cutting Speeds for Various Samples.

3.2 Performance of Probability of Cutting Tool Life at Various Cutting Speeds

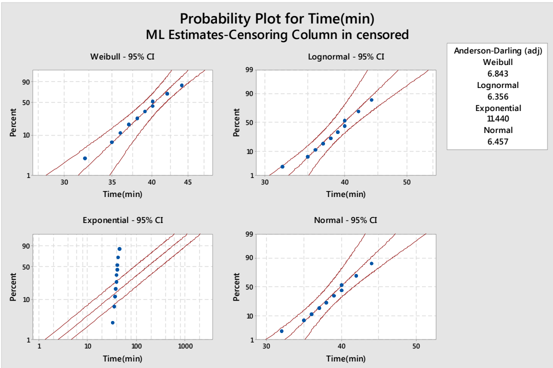
Before performing the reliability analysis, it is important to collect the data such as Flank wear at regular interval and time of the failure of samples. We have to check which distribution is fit for the given data.

Figure 2 shows that the various probability distribution plots of Failure Time at different cutting speeds namely 100,140,200, 280 and 400 m/min, similar plots were presented by Mykhaylo Frolov et al [17].

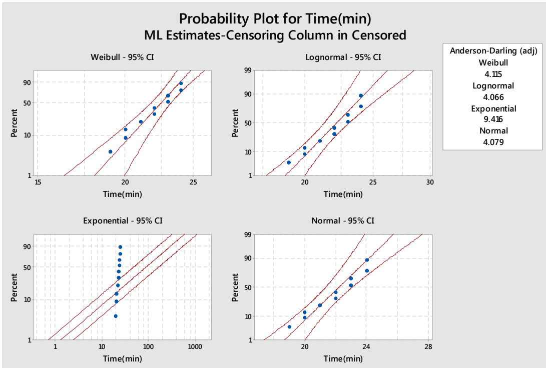
In reliability analysis, we take the failure time on X axis and Percentage failure value on y-axis. Various distributions were drawn in Figure 2.

Weibull distribution function is defined by two parameters, namely shape (shape of the graph) and scale (the larger the scale, the wider the graph). Lognormal distribution function is defined by two parameters location (mean is a function) and scale (the larger the scale, the wider the graph). Normal distribution is defined by two parameters mean and standard deviation.

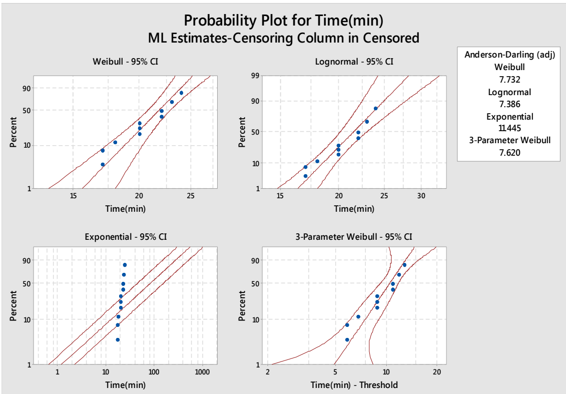
Weibull, lognormal, exponential and Normal distribution were used to fit the given data. By considering the goodness of fit (Anderson darling values), the plots were drawn. In most of the plots, Weibull, Normal and Lognormal distributions fit the data. This method was discussed by Fan Ning et al [18]



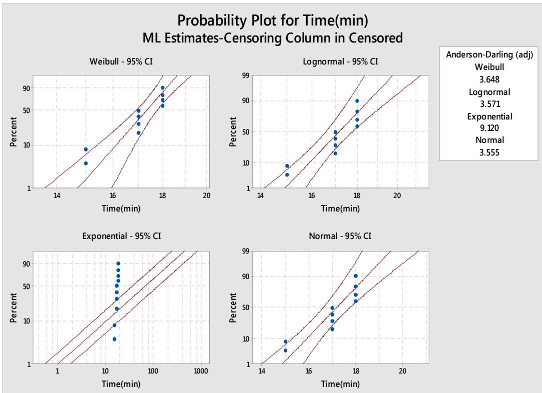
(a) Cutting Speed: 100 m/min



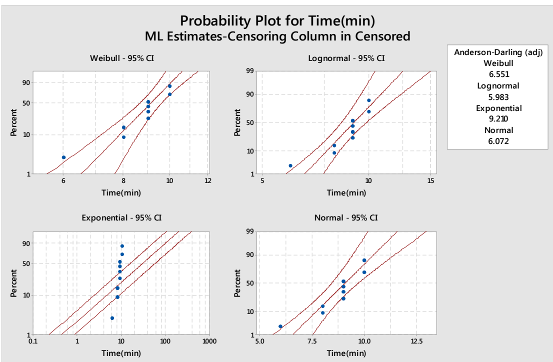
(b) Cutting Speed: 140 m/min



(c) Cutting Speed: 200 m/min



(d) Cutting Speed: 280 m/min



(e) Cutting speed: 400 m/min

Figure 2: Probability Plots for Time and Maximum Likelihood Parameter Estimates of Cutting Tool at Different Cutting Speeds.

3.3 Mean Time to Failure (MTTF) at Various Cutting Speeds

Mean time to failure (MTTF) at various cutting speeds is estimated through Distribution ID plot of right censoring method, using Minitab. MTTF of the cutting tools at 95% Normal confidence level are given for Weibull, Lognormal, Exponential and Normal distributions in Table-5. It has been observed that there is close correlation between mean, standard error and 95% normal confidence level for upper and lower deviations of tool life (measured in minutes) among Weibull, lognormal and normal.

However, exponential distribution, we found that standard error ranged from 12.49 to 76.87%, which itself is an indication that exponential distribution can't estimate the mean time to failure.

Table 5: Mean Time to Failure (MTTF) at Various Cutting Speeds at 95% Normal Confidence Level

Distribution	Mean, min	Standard Error	95% Normal Confidence Level	
			Lower	Upper
(a) Mean Time to Failure (MTTF) at Cutting Speed of 100 m/min				
Weibull	39.853	0.7562	38.398	41.363
Lognormal	40.001	0.9869	38.113	41.983
Exponential	243.100	76.8750	130.801	451.813
Normal	39.903	0.8973	38.144	41.662
(b) Mean Time to Failure (MTTF) at Cutting Speed of 140 m/min				
Weibull	22.278	0.3825	21.5405	23.040
Lognormal	22.244	0.4637	21.3535	23.172
Exponential	126.900	40.1293	68.2791	235.850
Normal	22.236	0.4390	21.3753	23.096
(c) Mean Time to Failure (MTTF) at Cutting Speed of 200 m/min				
Weibull	21.974	0.3967	21.2106	22.766
Lognormal	22.195	0.5898	21.0684	23.382
Exponential	120.600	38.1371	64.8894	224.141
Normal	22.103	0.5204	21.0827	23.123
(d) Mean Time to Failure (MTTF) at Cutting Speed of 280 m/min				
Weibull	17.2075	0.2265	16.7692	17.657
Lognormal	17.2033	0.3071	16.6118	17.816
Exponential	99.00	31.3065	53.2674	183.996
Normal	17.19	0.2898	16.267	17.763
(e) Mean Time to Failure (MTTF) at Cutting Speed of 400 m/min				
Weibull	8.9196	0.2537	8.4359	9.4310
Lognormal	9.0463	0.3911	8.3113	9.8463
Exponential	39.5000	12.4910	21.2532	73.4126
Normal	8.9707	0.3243	8.3350	9.6063

3.4 Goodness of Fit using Anderson-Darling Method

Anderson Darling goodness of fit measures the area between the fitted line and empirical distribution function, which is based on the data points. Here, the smaller value indicates that distribution follows the normal distribution, and large value gives us an idea about that it does follow the normal distribution.

Table 6: Goodness of Fit using Anderson-Darling Values

Cutting Speed (m/min)	Anderson-Darling(Adj) Values				Minimum Anderson-Darling(Adj) among Various Distributions
	Weibull	Lognormal	Exponential	Normal	
100	6.843	6.356	11.440	6.457	6.356
140	4.115	4.066	9.416	4.079	4.066
200	7.732	7.386	11.445	7.620	7.386

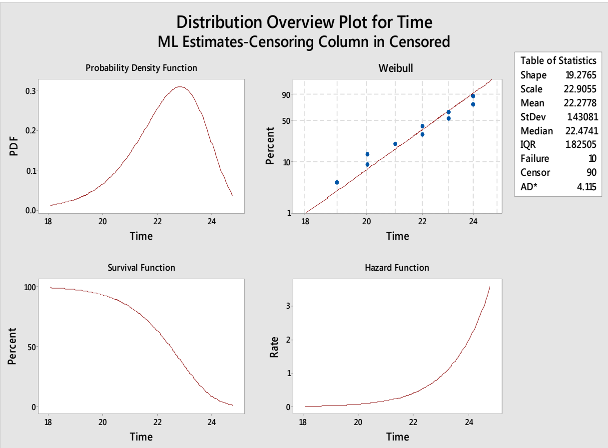
Table Contd.,					
280	3.648	3.571	9.120	3.55	3.571
400	6.551	5.983	9.210	6.072	5.983

Table 6 shows Goodness of Fit using Anderson-Darling values at various cutting speeds and minimum 'Anderson value' for each distribution at respective cutting speed is shown in the last column. It is demonstrating clearly that Anderson-Darling values for Weibull, Lognormal and Normal distributions are close to each other but Exponential distribution is far from other values. There is a close agreement within 10%among Weibull, Lognormal and Normal distributions. However, lognormal distribution has the lowest value indicating that it follows normal distribution. Among various values of Anderson-Darling, the value at cutting speed of 280m/min is lowest and has quite significance also from the point of view of metal removed per edge as this speed is more productive.

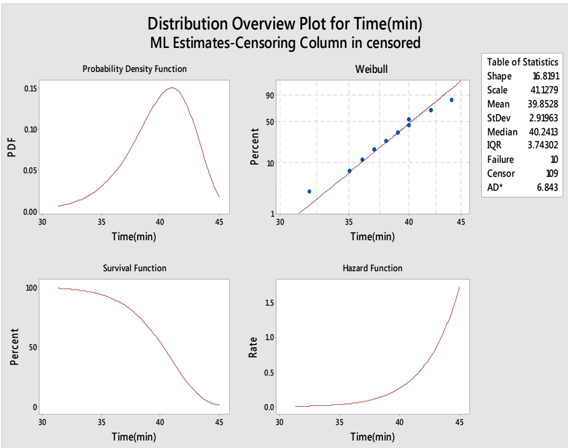
3.5 Probability Density Functions in Reliability

A probability density function of a failure time shows the relative probability of the failure time for a given value. A survival function of a failure time means that the probability of unit surviving at a particular period of time. A hazard function means that the probability of unit failing at that time, given that it is survived until then.

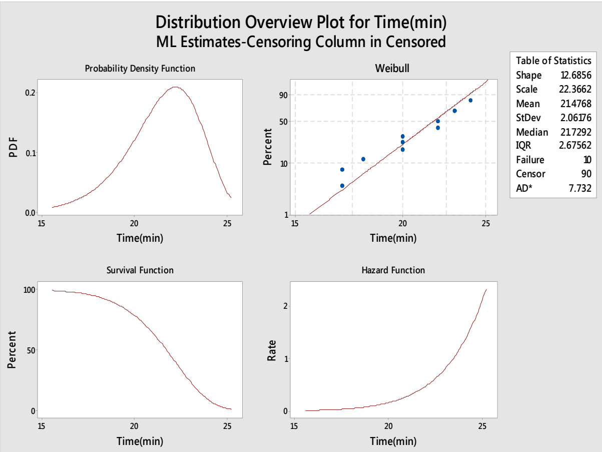
Figure 3 shows that the various probability distribution plots at different cutting speeds indicating Probability Density Function(PDF), Weibull, survival function and hazard functions. The similar distributions were previously carried by Michael Odigie et al [19] and Vigneau et al [20]. The results of these graphs are summarized in table 7.



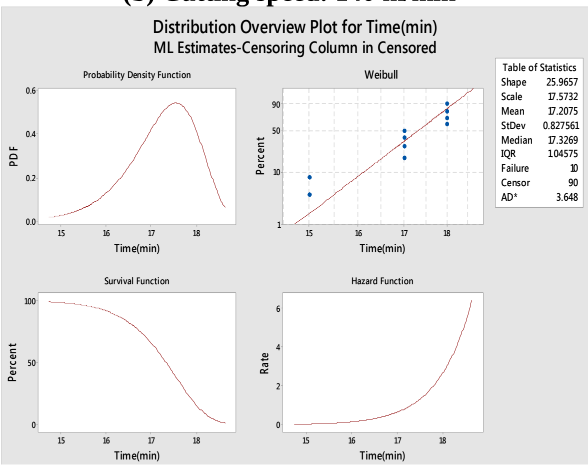
(a) Cutting speed: 100 m/min



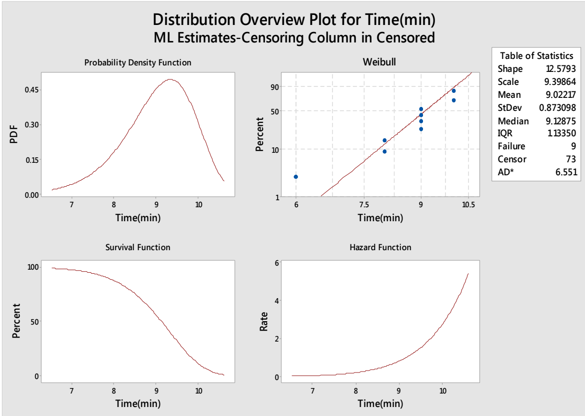
(b) Cutting speed: 140 m/min



(c) Cutting speed: 200 m/min



(d) Cutting speed: 280 m/min



(e) Cutting speed: 400 m/min

Figure 3: Distribution Overview Plot for Probability Density Function (PDF), Weibull, Survival Function and Hazard Functions Distribution at Various Cutting Speeds.

Table 7: Overview of Maximum Likelihood Estimates of the Probability Density Function (PDF), Weibull, Survival Function and Hazard Functions Distribution at Various Cutting Speeds

Cutting Speed (m/min)	Shape	Scale	Mean in min	Standard Deviation	Median in min	Inter-quartile range (IQR)	Failure in Count	Censoring
100	16.81	41.12	39.85	2.91	40.24	3.743	10	90
140	19.27	22.90	22.27	1.43	22.47	1.82	10	90
200	12.68	22.36	21.47	2.06	21.72	2.67	10	90
280	25.96	17.57	17.20	0.82	17.32	1.04	10	90
400	12.57	9.39	9.02	0.87	9.12	1.13	10	73

From Table 7, the parameters of Shape and Scale give insight into the nature of failure of the samples from Weibull plot.

Minitab estimates Shape and Scale parameters from the data. The shape parameter describes how the data are distributed. A shape of 3 approximates a normal curve. Lower shape values result in a right-skewed distribution, higher values result in a left-skewed distribution. The result at the various cutting speeds, ranging from 12.68 to 25.96, indicates left-skewed distribution.

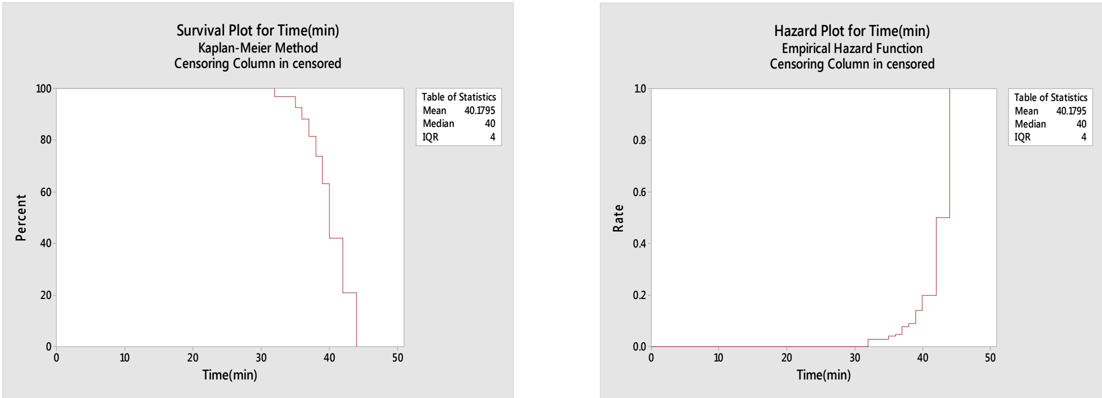
The scale parameter describes how spread out the data is. Generally, a larger scale results in a distribution that is more spread out. Here, the values range from 9.39 to 41.12, indicating the data is spread out mostly at cutting speeds of 100 m/min. At cutting speeds of above 100 m/min, the spread out is less and failure of the cutting tools is not random.

From the above results, we can conclude that fairy the tools are behaving consistently at all cutting speeds, and there is a variation at lower cutting speeds namely at 100m/min.

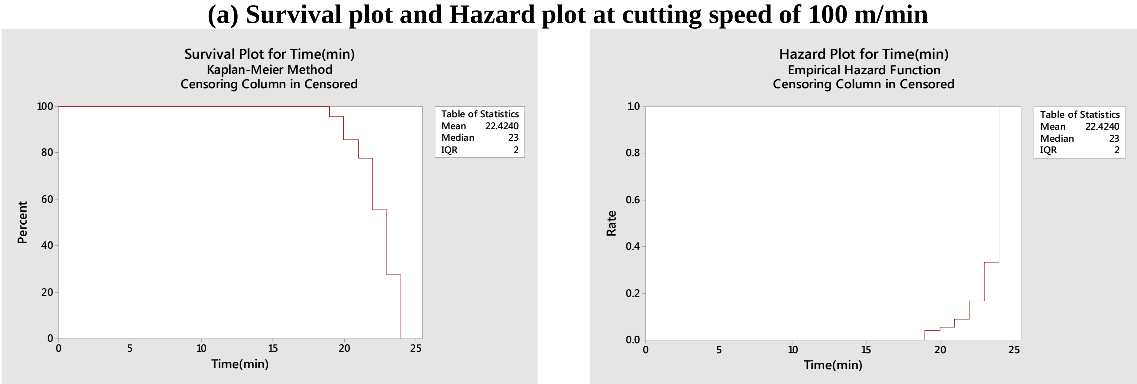
3.6 Survival Probability by Using the Kaplan-Meier Estimates

The Kaplan–Meier estimator, also known as the product limit estimator, is a non-parametric statistic used to estimate the survival function from lifetime data. The survival probability indicates the probability that the manufactured goods survive until a particular time. We use these values to determine whether the product meets reliability requirements or to compare the reliability of two or more designs of a product. Marcel Proust[21] has described their use extensively in different situations. The Kaplan-Meier estimation is a very useful tool for estimating survival function and Hazard functions.

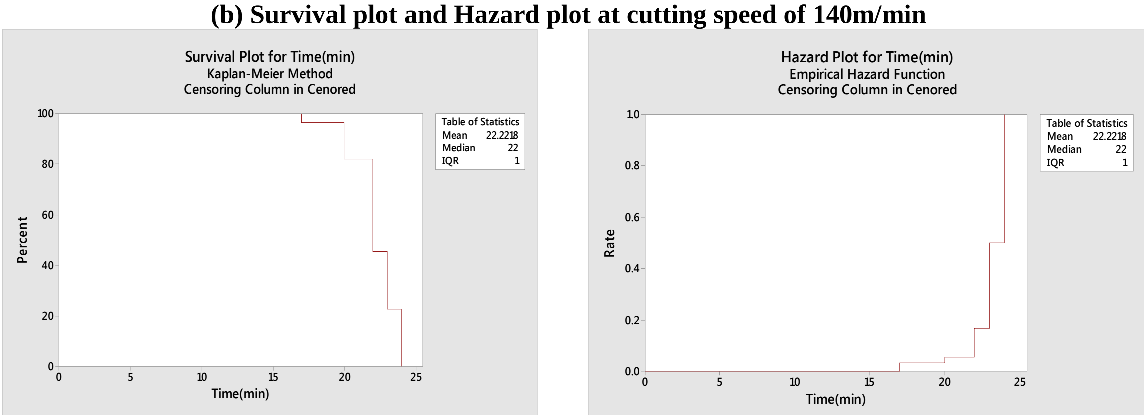
Figure 4 shows Kaplan-Meier estimates for survival and hazard plots at various cutting speeds. Table 8 summarizes the various Kaplan-Meier Estimates at different Cutting speeds.



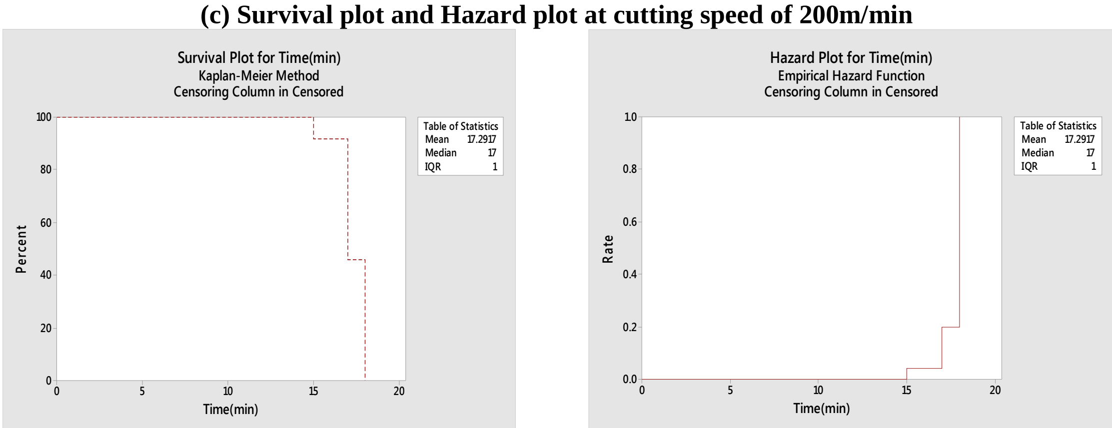
(a) Survival plot and Hazard plot at cutting speed of 100 m/min



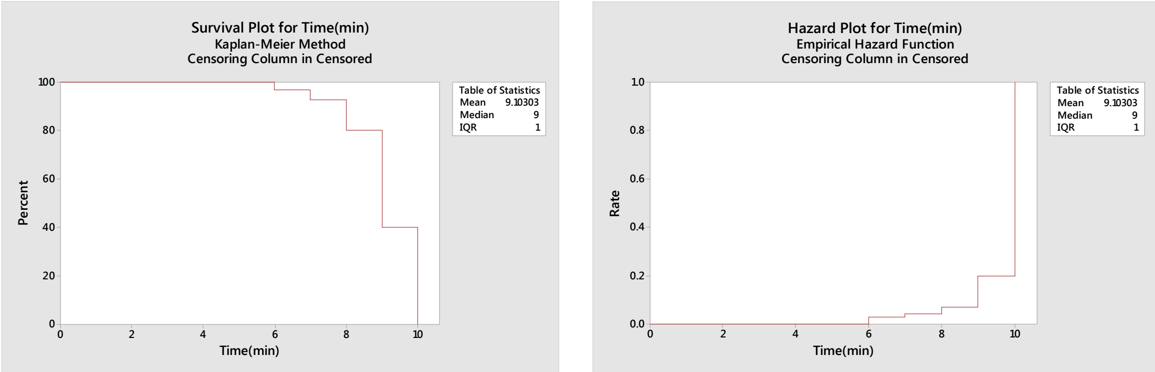
(b) Survival plot and Hazard plot at cutting speed of 140m/min



(c) Survival plot and Hazard plot at cutting speed of 200m/min



(d) Survival plot and Hazard plot at cutting speed of 280m/min



(e) Survival Plot and Hazard Plot at Cutting Speed of 280m/min

Figure 4: Kaplan-Meier Estimates for Survival and Hazard Plots at Various Cutting Speeds.

Table 8: Kaplan-Meier Estimates at Various Cutting Speeds

Cutting speed in (m/min)	Actual Failure Time(min)	Survival probability of more than 90 % out of 10 tool tips			Standard Error in (%)	95 % confidence level	
		Time in (min)	Number Failed	Survival Probability in (%)		Lower	Upper
100	40	32	1	97.5	0.02	0.91	1.000
140	23	19	1	95.6	0.07	0.87	1.000
200	22	17	1	96.8	0.03	0.89	1.000
280	17	15	2	91.6	0.05	0.80	1.000
400	8	6	1	96.9	0.02	0.91	1.000

Kaplan-Meier estimates of the survival probability vary from 91.6 to 97.5% at for the cutting speeds ranging from 100 to 400 m/min with an error of 0.02 to 0.07 %. This again proves that majority of the tools survived (>90%) for 80% of estimated tool life of best performing tool. The consistency in tool life is achieved at all cutting speeds.

3.7 Metal Removal per Edge

A graph is drawn Metal removed vs. Cutting speed for speeds ranging from 100 m/min to 400 m/min, and shown in Figure 5.

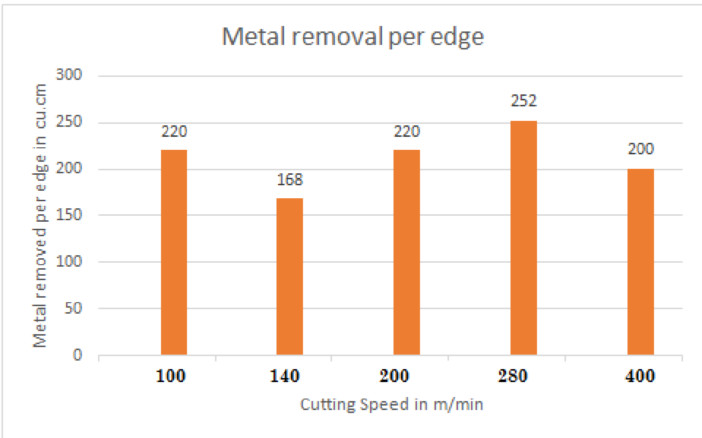


Figure 5: Metal Removal per Edge at Various Cutting Speeds.

Figure 5 shows the material removed per edge at various cutting speeds. It is found that removal of material is observed that 252 cu.cm at 280 m/min cutting speed. From the tool life, it is understood that the metal removal of this volume is possible at the shortest time and hence this would be economical.

4. CONCLUSIONS

The following conclusions can be made from the above results. They are

- The tool flank wear will increase with cutting time. The results of the experimental studies have indicated that cutting speed is having remarkable effect of the tool life. The faster cutting speed will cause faster degradation of tool life leads to shorter tool life.
- ZTA samples prepared by Powder Processing Technique have performed well with good consistency at all cutting speeds and 280 m/min speed is an ideal speed. However, 200-400 m/min range can be recommended for high speed machining applications.
- Reliability analysis has been applied to cutting tools samples by using the Minitab software. Weibull, lognormal and normal distributions are best fit for the given data. Goodness of Fit using Anderson-Darling technique for Weibull, Lognormal and Normal distributions are close to each other, but Exponential distribution is far from other values. There is a close agreement within 10% among Weibull, Lognormal and Normal distributions.
- Right censoring methods is used for finding out the survival probability of these cutting tools. Kaplan-Meier estimates of the survival probability vary from 91.6 to 97.5% for the cutting speeds ranging from 100 to 400 m/min, which is well within 0.07 %. This again establishes the consistency in tool lifeof majority of the tools (90%) survived more than 80% of estimated tool life of best performing tool.

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